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A sizing strategy for the Advanced Modular Multi-threat Protective Headwear System

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Canada

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Abstract

The Advanced Modular Multi-threat Protective Headwear System Technical Demonstration Project (AMMPHS TDP) aims to "provide improved blast, ballistic, and impact protection as well as modular and scalable coverage for mounted and dismounted operations". New concepts are being proposed to achieve this and the challenges are numerous from materials to design aspects. One of the challenges facing this project is to ensure that the helmet system will fit its intended population and provide the degree of coverage and protection required.

A new tool was created that condensed a large amount of three-dimensional (3D) laser scan data and made it easily accessible. This new tool provides a glimpse into the internal structure of the data and provides unparalleled knowledge of the main modes of variation of Canadian Forces (CF) head shapes. From this, a set of design head forms was derived that captures about 50% of this variability and allows designers to build in the necessary adjustments.

While the proposed strategy captures roughly 50% of the variability, the next step would be to examine a few more of the principal components, assess their relevance to the design of the AMMPHS, and compare the head forms generated in this way with the ones proposed herein. The goal would be to determine whether or not they provide additional information.

Résumé

AMMPHS est un TDP qui vise à fournir une meilleure protection balistique contre l'impact ainsi qu'une protection modulaire et évolutive pour les soldats. De nouveaux concepts sont proposés pour atteindre cet objectif et les défis à relever sont nombreux à partir des matériaux jusqu'aux aspects de la conception. L'un des défis de ce projet est de faire en sorte que le système de casque soit bien adapté à la population des utilisateurs et d'assurer un degré de couverture convenable.

Un nouvel outil a été créé qui a condensé une grande quantité de données laser 3D et l'a rendue facilement accessible. Ce nouvel outil offre un aperçu de la structure interne des données et fournit des connaissances sans précédent des principaux modes de variation des têtes des soldats des forces canadiennes. Un ensemble de formes de tête a été créé capturant près de 50% de cette variabilité et permet aux concepteurs de fournir les ajustements nécessaires.

Bien que la stratégie proposée capte environ 50% de la variabilité, la prochaine étape serait d'examiner un plus grand nombre de composantes principales, d'évaluer leur pertinence pour la conception de AMMPHS, et de comparer les formes de têtes ainsi générées avec celles qui sont proposées dans ce document. L'objectif serait de déterminer si elles fournissent des informations supplémentaires.

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Executive summary

A sizing strategy for the Advanced Modular Multi-threat Protective Headwear System Technical Demonstration Project (AMMPHS TDP):

Pierre Meunier; DRDC Toronto TM 2008-176; Defence R&D Canada – Toronto; June 2010.

Introduction or background: The Advanced Modular Multi-threat Protective Headwear System Technical Demonstration Project (AMMPHS TDP) aims to "provide improved blast, ballistic, and impact protection as well as modular and scalable coverage for mounted and dismounted operations". Totally new concepts are being proposed to achieve this and the challenges are numerous from material choices to design aspects. One of the challenges facing this project is to ensure that the helmet system will fit its intended population and provide the degree of coverage and protection required.

Results: The Gallet helmet sizing system was reviewed and analysed. Its design strategy was found to be sound and well adapted to the Canadian Forces (CF) population. The lessons learned from the analysis were as follows:

1. Three sizes appear to be sufficient to accommodate the CF population, at least from a helmet shell perspective

2. The Medium shell size should center on the male population, and the Small on the female.

3. The Large shell appears too short (lengthwise) and should be made longer in the AMMPHS.

A new tool was created that condensed a large amount of three-dimensional (3D) laser scan data and made it easily accessible. This new tool provides a glimpse into the internal structure of the data and provides unparalleled knowledge of the main modes of variation of CF head shapes. From this, a set of design head forms was derived that captures about 50% of this variability and allow designers to build in the necessary adjustments.

Significance: A set of head forms was generated along with a design strategy that can form the basis of the AMMPHS sizing system.

Future plans: While the proposed strategy captures roughly 50% of the variability, the next step would be to examine a few more of the principal components, assess their relevance to the design of the AMMPHS, and compare the head forms generated in this way with the ones proposed herein. The goal would be to determine whether or not they provide additional information.

Sommaire

A sizing strategy for AMMPHS:

Pierre Meunier; DRDC Toronto TM 2008-176; R & D pour la défense Canada – Toronto; Octobre 2008.

Introduction ou contexte: AMMPHS est un TDP qui vise à fournir une meilleure protection balistique contre l'impact ainsi qu'une protection modulaire et évolutive pour les soldats. De nouveaux concepts sont proposés pour atteindre cet objectif et les défis à relever sont nombreux à partir des matériaux jusqu'aux aspects de la conception. L'un des défis de ce projet est de faire en sorte que le système de casque soit bien adapté à la population des utilisateurs et d'assurer un degré de couverture convenable.

Résultats: Un nouvel outil a été créé qui a condensé une grande quantité de données laser 3D et l'a rendue facilement accessible. Ce nouvel outil offre un aperçu de la structure interne des données et fournit des connaissances sans précédent des principaux modes de variation des têtes des soldats des forces canadiennes. Un ensemble de formes de tête a été créé capturant près de 50% de cette variabilité et permet aux concepteurs de fournir les ajustements nécessaires.

Importance: Un certain nombre de formes de tête a été généré ainsi qu'une stratégie de conception qui peuvent constituer la base du système de tailles de AMMPHS

Perspectives: Bien que la stratégie proposée capte environ 50% de la variabilité, la prochaine étape serait d'examiner un plus grand nombre de composantes principales, d'évaluer leur pertinence pour la conception de AMMPHS, et de comparer les formes de têtes ainsi générées avec celles qui sont proposées dans ce document. L'objectif serait de déterminer si elles fournissent des informations supplémentaires.

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1 Introduction

The Advanced Modular Multi-threat Protective Headwear System Technical Demonstration Project (AMMPHS TDP) aims to "provide improved blast, ballistic, and impact protection (over the currently used Canadian Forces helmet manufactured by Gallet Sécurité Internationale) as well as modular and scalable coverage for mounted and dismounted operations". Totally new concepts are being proposed to achieve this and the challenges are numerous from material choices to design aspects. One of the challenges facing this project is to ensure that the helmet system will fit its intended population and provide the degree of coverage and protection required. The purpose of this Technical Memorandum is to address the helmet sizing issue and provide a design strategy.

2 Review of the Gallet helmet sizing

The Gallet helmet, currently used by the Canadian Forces (CF), comes in three sizes: Small, Medium, and Large. The assignment of helmet size is determined on the basis of Head Length, Head Breadth, and Head Circumference. In reality, since Head Circumference is highly correlated with the other two (Pearson correlation r ~ 0.9) and is of value mostly for the sizing of the head band, Head Breadth and Head Length are the critical variables of interest. For that reason, Head Circumference will be ignored in the subsequent review and analysis.

The cut-off values for the various helmet sizes, according to the user manual[1], are listed in Table 1. For some reason, the difference between the Small and Medium limits is larger than that between the Medium and Large.

Table 1 Nominal Gallet sizing criteria – upper values

Size	Head Length (HL in mm)	Delta HL (mm)	Head Breadth (HB in mm)	Delta HB (mm)
Small	193		148	
		12		12
Medium	205		160	
		10		10
Large	215		170	

To see how these numbers compare with the CF population, or, in other words, to see how much of the population is accommodated by the sizing system, a bivariate plot was prepared (Figure 1). This shows male and female data from the 1997 survey of the land forces, hereafter referred to as the LF97 survey (Chamberland, Carrier, Forest, & Hachez, 1998), with an overlay of the sizing limits represented by three sets of horizontal and vertical lines, each one identifying the upper limits for the Large, Medium, and Small helmets.

An interesting insight into Gallet's sizing strategy is provided when the sizing criteria are drawn on histograms of the male and female populations, as shown in Figures 2 and 3. From these histograms, it is apparent that Gallet aimed the Medium helmet on the peak of the male population. The proof of that is in Table 2, where it is shown that the lower and upper limits of the helmet – the lower limit being the upper limit of the Small helmet - coincide with the mean plus or minus one standard deviation (± 1 s.d.) of the land forces males within a millimetre or two. As it turns out, the mean + 1 s.d. for females corresponds almost exactly to the mean – 1 s.d. for males, which makes it convenient to center the Small helmet on the peak of the female

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[1] http://hem.bredband.net/runmat3/Manuals/ca-cg634/ca-cg634.html

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population. This is a very sensible approach (not to mention a fortuitous coincidence) in that it is the most likely to provide an optimum fit for the bulk of the two populations.

One of the attributes of the sizing system is that both the Small and Medium helmets cater to the other gender as well. This is not the case for the Large, as it caters to the upper tail of the distribution for both variables and therefore targets almost exclusively the male population. One observation that can be made from Figure 1 is that it appears to exclude more males on the basis of Head Length than on the basis of Head Breadth. A closer look reveals that the Head Length limit corresponds to the 99.1 percentile whereas the Head Breadth limit corresponds to the 99.9 percentile. This represents an imbalance that could have been corrected had the helmet length been increased by 5 mm, to make it correspond with the 99.9 percentile Head Length. It may explain why it was necessary to design and produce an X-Large helmet after the initial purchase.

Figure 1 Gallet helmet sizes (vertical and horizontal lines represent the limits) versus Head Length and Head Breadth - LF97 survey

Figure 2 Gallet Head Length sizing criteria (vertical lines) vs. CF population histogram

GENDER: Male HEAD_BRE = 465*5*normal(x, 152.8022, 5.4669)
GENDER: Female HEAD_BRE = 243*5*normal(x, 146.2922, 4.8805)

No of Observations

Medium

Small

Large

125 130 135 140 145 150 155 160 165 170 175 180

Head Breadth (mm)

GENDER: Male
GENDER: Female

Figure 3 Gallet Head Breadth sizing criteria (vertical lines) vs. CF population histogram

Table 2 Comparison of lower and upper limits of the Medium helmet vs. the land forces male population (LF97 survey)

	LF97 Males Mean - 1 s.d.	Small helmet	LF97 Females Mean + 1 s.d.	LF97 Males Mean + 1 s.d.	Medium helmet
Head Breadth (mm)	147	148	151	158	160
Head Length (mm)	192	193	194	206	205

The sizing rules were established to ensure that the wearers maintain a stand-off distance of at least 12 mm to allow for back face deformation and airflow - cooling. It takes into account the suspension system, the integrated impact protection (rigid and soft foam), and the shape of the shell. The purpose of this portion of the review of the Gallet sizing system is to look at the geometrical differences between the shells themselves to see how well they correlate with the head sizing limits.

All three sizes of helmet were scanned inside and out using a three-dimensional (3D) laser scanner. An example of this is shown in Figure 4, with the wireframe display giving the appearance of an x-ray. Some of the features, such as the headband, suspension system, and some of the inside shell and foam liner, are visible. The view shown is orthogonal, which means that there is no perspective distortion and that measurements can be made directly. It is worth pointing out that the suspension system is not in its as-worn position – it is sagging somewhat. When worn, it stretches out closer to the dotted line (identified as the Foam liner in Figure 4).

Figure 4 Medium helmet scan

Comparison of the helmet geometries requires a common basis or a reference point. Two ways of comparing the geometries were selected: one in which the shells are concentric and one where the headbands are co-located. Both comparisons are valid for different reasons. In the first instance, the comparison provides an insight into Gallet's approach to geometric scaling, whereas in the second, the comparison provides insight from a wearer's perspective. It is interesting to note that the flare at the rear of the helmet is slightly more pronounced in the Small helmet than for the other two sizes.

When the shells are placed concentrically, as shown in Figure 5, they appear to have the same base and a uniform scaling that starts from there. When the helmets are aligned based on the headband (Figure 6), the shells appear to have a common top and provide progressively more coverage as the size increases. The Small helmet appears to be slightly different in that it tilts more upward than the other two sizes, although this may be an artefact produced by the loose headband material.

Figure 5 Helmet size comparison, concentric shells

Figure 6 Helmet size comparison, common headband position

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The previous section examined the helmet shell sizes and provided insight into the scaling scheme. The question that arises from these observations is whether or not the change in helmet shape and size follows the pattern of head variability of the population it is intended to fit. To explore this, three head forms were created using representative statistical shapes from the LF97 survey. The software used for this, Principal Components Analysis (PCA) Creator[2] is a statistical shape analysis tool that captures the main modes of head variability by order of importance. The first principal component, PC1, which captures the main mode of variation, was used to create three heads at the upper limit of the Small, Medium, and Large helmets. The result is depicted in Figure 7 where the head shapes – from the male dataset in this case – were superimposed onto the bivariate plot of Head Length and Head Breadth and the established limits of helmet sizing. The heads depicted can be viewed as the most probable head shape for those head lengths and breadths. What is new and important about this is that all of the 3D points on the head vary in accordance with their correlations with the overall head size. It is obvious from Figure 7 that it is not a simple scaling of the head, which would produce the same shape for any size, but a more complex and realistic representation of the population. Thus, the smaller head tends to have a thinner jaw, whereas the larger ones tend to have progressively stronger jaws.

Figure 7 Head shape and size in relation to helmet sizing

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[2] This software is the property of the National Research Council, but the data are those of DRDC/DND.

Figure 8 shows an overlay of the three head forms based on concentric positioning. Shown are the 1st, 50th, and 99th percentiles for males on the PC1. It is interesting to note that with this alignment method the facial features, such as the eyes, nose and middle of the ear, remain fairly well aligned independent of their size. This means that in the general case, the helmet shells should be sized from a common brim position, just as Gallet did and as depicted in Figure 5. It can be concluded that the Gallet sizing system is consistent with the principal – i.e., PC1 – mode of head variation and therefore provides optimal coverage for each subset of the population.

Figure 8 Comparison of heads from a common eye level

Putting the results of the previous two sections together, it is possible to assess how well the helmet shells fit the heads. Figure 9 shows a virtual[3] fit of the helmets with the largest head size for each helmet category. The concentrically positioned helmets were overlaid onto the concentrically positioned heads and isolated one by one in the vignettes of Figure 9. All vignettes are shown to scale and are directly comparable. The results show an almost perfect match in

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[3] Virtual in the sense that the positioning of the helmet on the head is not based on a wearer's preference but on a graphical best-fit.

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coverage and positioning of the helmets. This is remarkable given the fact that Gallet did not have the benefit of tools such as the PCA Creator and head scan data of the LF97 anthropometric survey for the design of their helmet, but this is not too surprising considering the decades of experience of the company. The only fault would seem to be that the largest helmet is undersized, a fact that was predictable from Figure 1 and almost visible in Figure 9.

Figure 9 Virtual helmet fit for Small, Medium and Large helmets

3 An AMMPHS design strategy

3.1 Dealing with more complexity

On a design complexity scale, the Gallet helmet shell would rate lower than the AMMPHS. The reason for this, it is argued, is that the main purpose of the Gallet helmet is to cover the cranium whereas the AMMPHS' purpose is to protect the entire head, as shown in Figure 10 . It is not that the variability of the face is ignored in the Gallet helmet design but that simpler information is sufficient for most of its features. For instance, a single dimension is sufficient to determine the length of the chin strap.

The situation is different for the AMMPHS, and designers will require knowledge of the 3D variability of the whole head to decide on the shape, size and possible adjustment range of features, for example, such as for mandibular protection. To achieve optimal results, a fundamental understanding of the shape and size of CF heads is required, and it is only recently that this has become available.

Figure 10 Early AMMPHS design concept in four configurations

Through a joint effort with NRC[4] a software tool representing CF heads, called PCA Creator, was developed that provides this understanding and enables the creation of head forms that designers can use. It allows head forms to be created along the main modes of variation of the dataset, or principal components (PCs), or through combinations of PCs. One way of looking at PCs is to think of them as representing the internal structure of the data. PC1 explains the main mode of variability of the 3D data, PC2 explains most of the remainder of the variability, and so on. Figure 11 shows the percentage of variability expressed by the first ten PCs.

One of the properties of PCs is that they are orthogonal, which means that the variability expressed by each one can simply be added to provide an overall account of what is being captured. A plot of the cumulative variability explained by the PCs in Figure 12 shows that the first two PCs explain roughly half of the variability contained in the LF97 male dataset; the following eight explain about 30%.

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[4] NRC refers to the National Research Council of Canada's Institute of Information Technology; this project was carried out under the umbrella of a DRDC-NRC Memorandum of Understanding

While the analysis of the Gallet sizing system focused on PC1, a few more PCs would have provided good test cases to determine the adequacy of the head band, crown, and chin strap adjustment ranges. The AMMPHS, due to its features, will definitely require careful consideration of several PCs if it is to accommodate the CF population. The question is: which ones and in what combination are they representative?
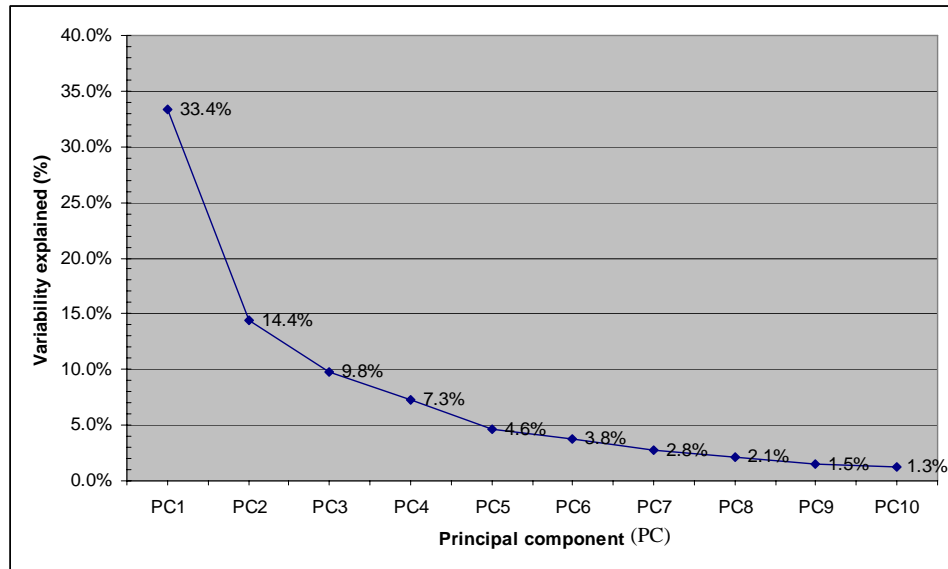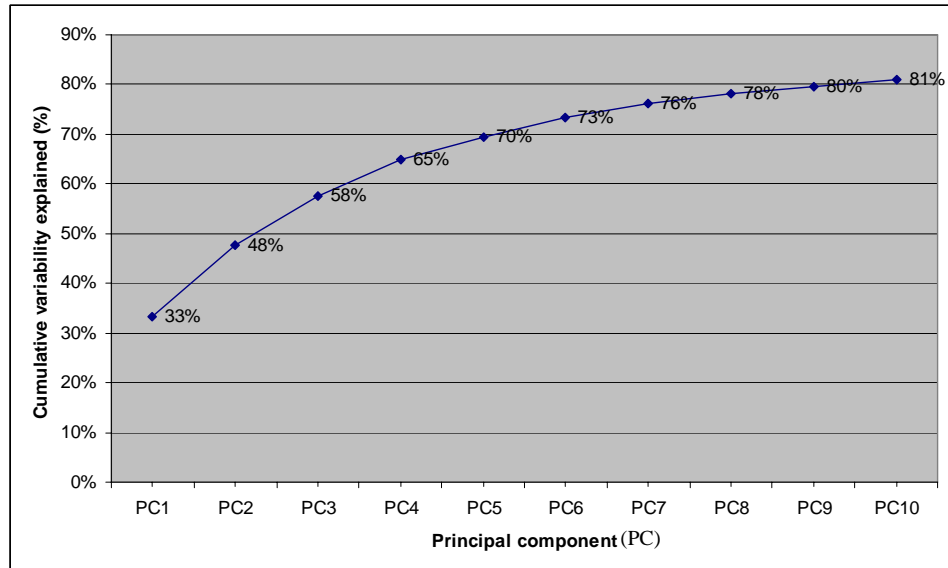

Figure 11 Scree plot for LF97 males

Figure 12 Cumulative variability explained by PCs 1 to 10

3.2   A design strategy for the AMMPHS

The brute force approach to dealing with population accommodation would have been to provide all of the raw head scans to the designers and allow them to perform exhaustive testing and evaluation of their design. Although this is possible, it is not the most efficient way to proceed as there is a multitude of redundant cases in the center of the distribution. At the other extreme, and this is perhaps the most commonly used method, another approach is to provide a single head form for a given helmet size. Designers could, for instance, design for the biggest head for a given shell size. This will work in some cases, such as in the design of a doorway for instance, but experience has shown that this method falls short when the relationship between the item and the human is more complex. Ideally, the variability of the population should be represented at the design stage by means of a limited number of carefully selected test cases. The selection of the cases should be based on knowledge of the population variability and of the design features. In other words, the test cases are design dependent.

An expansion of Figure 7, in which only PC1 is represented, can be made to explore the outer edges of the Head Length and Head Breadth bivariate distribution by combining the two main modes of variation; i.e., PC1 and PC2. A proposed strategy for conveying population variability to the designers is shown in Figure 13. In this strategy, head forms were created along the upper and lower limits of the helmet size to provide minimal and maximal test cases. The Gallet sizing system was used to illustrate the concept. Of the nine cases, S2, M2 and L2 are scaled purely on PC1, as in Figure 7. The other six cases are extremes of PC2, with PC1 adjusted to attain the appropriate Head Length and Head Breadth values at the edge of the sizing limits. The advantage of this scheme is that the test cases are dual purpose: the upper limit of one size can serve as the lower limit of the next size up.

It is difficult to appreciate the extent of the geometric differences between wearers of a given helmet size, unless 3D tools are used. Consider the head forms S1, S2 and S3. S1 and S2 are similar in Head Length, while S2 and S3 are similar in Head Breadth. However, along with the changes in these two anthropometric variables comes a significant morphological change in facial features. A comparison of head shapes using a 3D overlay of those head forms in pairs, as in Figure 14, gives a better appreciation for variation, at least at one end of the helmet's sizing limits. For instance, it is apparent that the difference between S1 and S2 is mainly at the jaw line. The comparison of S2 and S3 shows a more uniform difference between the two and points to the need for a substantial vertical adjustment of the helmet position and the potential for mandibular protection adjustment.

The true design challenge, however, is for the Medium helmet design to accommodate both the S and M head forms. In comparing the various S and M head forms in 3D, the largest contrast is found by comparing the largest wearer of the Medium helmet, M2, with its smallest, S1 and S3. This is represented in Figure 15, where the size and shape appear to be compounded relative to Figure 14. Those three head forms give a fairly complete picture of the extent of the variability contained within the Medium helmet user population, at least for the first two PCs. Hence, accommodating heads M2, S1 and S3 would constitute the most efficient way to design a medium sized AMMPHS helmet. The dotted triangles in Figure 153 show how the head forms could be used in triads for efficiency; M2, S1 and S2 for the Medium helmet, and L2, M1 and M2 for the Large.
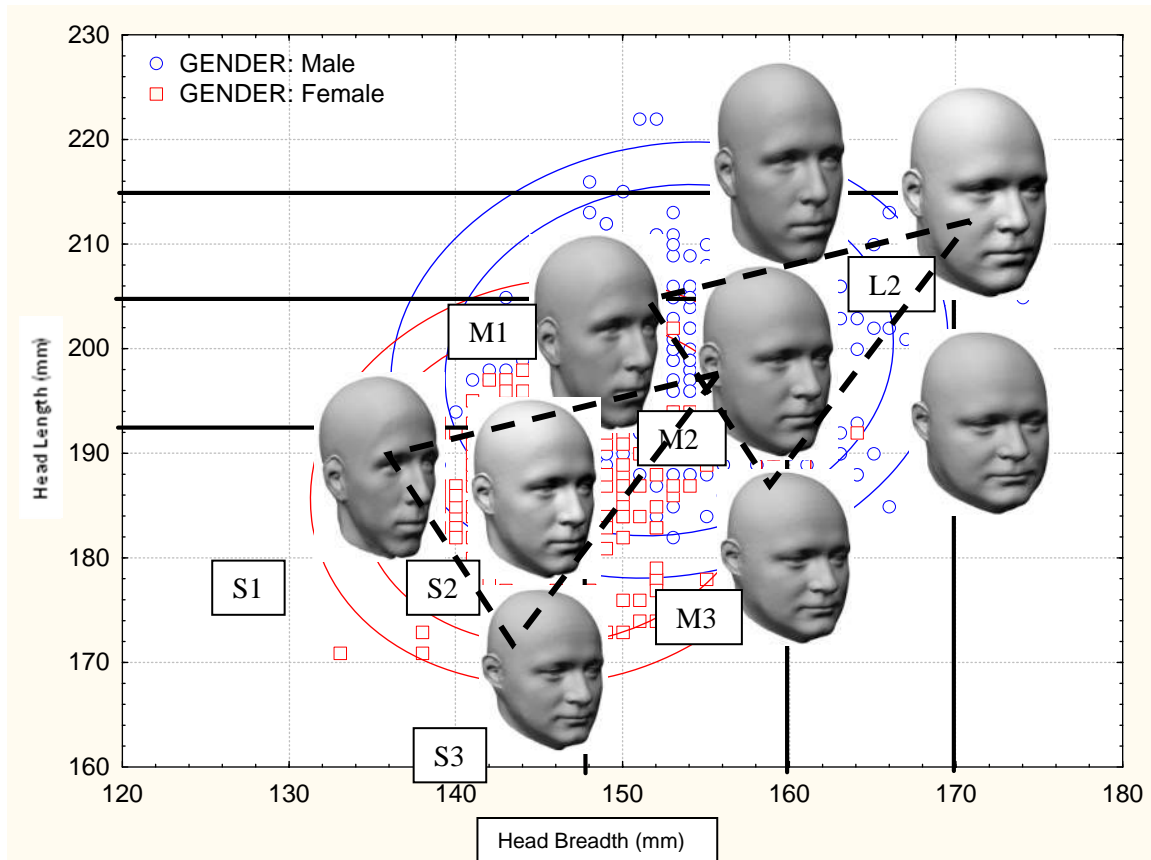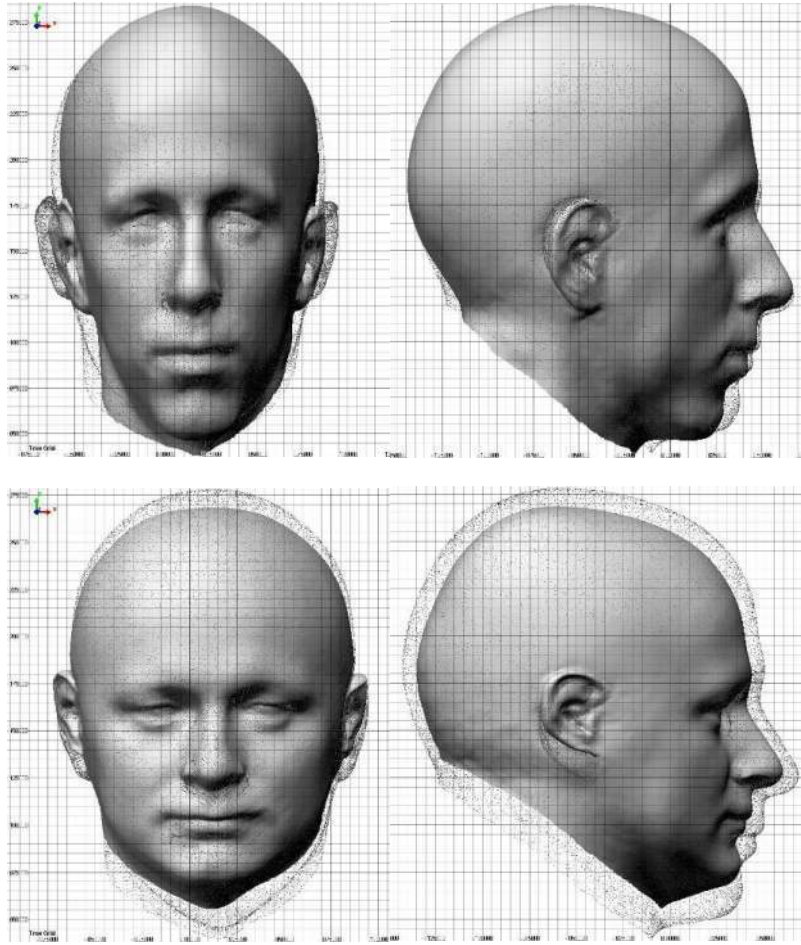
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Figure 13 Test cases based on principal components 1 and 2

Figure 14 Front and side comparisons of S1-S2 (Top) and S2 -S3 (Bottom) with common eye level - S2 shown as semi-transparent
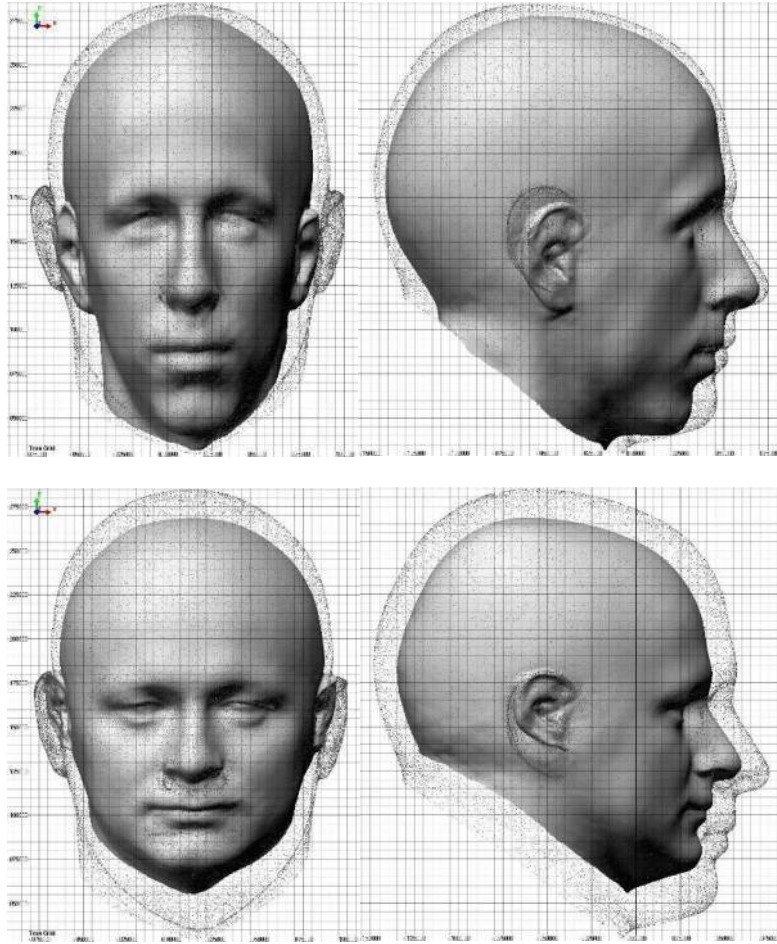
Figure 15 Front and side comparisons of M2-S3 (Top) and M2-S1 (Bottom) with common eye level - M2 shown as semi-transparent

Conclusions and recommendations

The Gallet helmet sizing system was well conceived and should be used as inspiration for the design of the AMMPHS. The lessons learned from the analysis provided in this report are as follows:

1. Three sizes appear to be sufficient to accommodate the CF population, at least from a helmet shell perspective

2. The Medium shell size should center on the male population, and the Small on the female.

3. The shells should be designed for the 1st, 50th, and 99.9^{th} percentile male head forms based on PC1.

A new tool was created that condensed a large amount of 3D laser scan data and made it easily accessible. This new tool provides a glimpse into the internal structure of the data and provides unparalleled knowledge of the main modes of variation of CF heads. From this, a set of design head forms can be derived that captures this variability and allows designers to build in the necessary adjustments.

A set of head forms was generated and analysed with helmet design in mind. This resulted in the proposal of an efficient design strategy for the AMMPHS. While the proposed strategy captures roughly 50% of the variability, the next step would be to examine a few more of the PCs, assess their relevance to the design of the AMMPHS, and compare the head forms generated in this way with the ones proposed herein. The goal would be to determine whether or not they provide additional information to designers.

References

Chamberland, A., Carrier, R., Forest, F., & Hachez, G. (1998). *Anthropometric survey of the Land Forces (LF97)* (Contractor report No. 98-CR-15). Toronto, Ontario: Defence and Civil Institute of Environmental Medicine.

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List of symbols/abbreviations/acronyms/initialisms

[Enter list here, if applicable. If not, delete the page.]

± s.d.	Plus or minus one standard deviation
3D	Three-dimensional
AMMPHS	Advanced Modular Multi-threat Protective Headwear System
CF	Canadian Forces
DND	Department of National Defence
DRDC	Defence Research & Development Canada
HB	Head Breadth
HL	Head Length
L1, L2, L3	Boundary heads for the Large helmet
LF	Land Forces
LF97	Anthropometric survey of the Land Forces, dated 1997
M1, M2, M3	Boundary heads for the Medium helmet
NRC	National Research Council
PC	Principal Component
PC1, PC2	Principal Components 1 and 2
PCA	Principal Components Analysis
R&D	Research & Development
S1, S2, S3	Boundary heads for the Small helmet
TDP	Technical Demonstration Program

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AMMPHS est un TDP qui vise à fournir une meilleure protection balistique contre l'impact ainsi qu'une protection modulaire et évolutive pour les soldats. De nouveaux concepts sont proposés pour atteindre cet objectif et les défis à relever sont nombreux à partir des matériaux jusqu'aux aspects de la conception. L'un des défis de ce projet est de faire en sorte que le système de casque soit bien adapté à la population des utilisateurs et d'assurer un degré de couverture convenable.

Un nouvel outil a été créé qui a condensé une grande quantité de données laser 3D et l'a rendue facilement accessible. Ce nouvel outil offre un aperçu de la structure interne des données et fournit des connaissances sans précédent des principaux modes de variation des têtes des soldats des forces canadiennes. Un ensemble de formes de tête a été créé capturant près de 50% de cette variabilité et permet aux concepteurs de fournir les ajustements nécessaires.

Bien que la stratégie proposée capte environ 50% de la variabilité, la prochaine étape serait d'examiner un plus grand nombre de composantes principales, d'évaluer leur pertinence pour la conception de AMMPHS, et de comparer les formes de têtes ainsi générées avec celles qui sont proposées dans ce document. L'objectif serait de déterminer si elles fournissent des informations supplémentaires.

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